Flavored gauge symmetry in SUSY

as origin of a discrete symmetry

(work in progress)

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Discrete symmetry (Z_N) from a gauged $U(1)$ in SUSY

Typical example:

$$U(1)_{B-L} \longrightarrow R_2 \qquad \text{(R-parity; } Z_2\text{)}$$

Our model:

$$U(1)_{B-x_iL} \longrightarrow B_3 \qquad \text{(Baryon triality; } Z_3\text{)}$$

(x_i = family-dependent values)

Remark:

It is a follow-up of the "$U(1)_{B-x_iL} \longrightarrow R_2$" paper [HL, Ma (2010)].

Outline

1. Model: Minimal $U(1)$-extended SUSY model with B_3
2. LHC Implications: Flavor-sensitive signals
3. Summary

Model

B_3 (baryon triality)

Z_3 symmetry suggested by Ibanez and Ross (1992) to avoid dim 5 proton decay operators ($QQQL$, $U^cU^cD^cE^c$) allowed in R-parity

Field	Q	U^c	D^c	L	N^c	E^c	H_u	H_d	meaning
B_3 charge	0	1	-1	1	0	1	-1	1	$-B + 2Y \bmod 3$

Selection rule (for any operator) : $\Delta B = 3 \times$ integer

(1) B : violated only by $3 \times$ integer.

(2) L : violated freely (λLLE^c, $\lambda' LQD^c$, $\mu' LH_u$ are allowed).

Proton decay ($\Delta B = 1$) is forbidden.

Goal

Construct a TeV-scale $U(1)$-extended SUSY model (w/o R-parity)

with (i) $U(1) \to B_3$

(ii) minimal particle contents

(i) B_3 (baryon triality)

— Alternative Z_N to R-parity for proton stability

(ii) Minimal particle contents (same as minimal $U(1)_{B-L}$)

— Spectrum: MSSM + 3 RH ν + Z' + $\underbrace{S_1,\ S_2}_{\text{(anomaly-free)}}$

$\rightarrow$ $U(1)$ charges should be family-dependent.

Additional $U(1)$ gauge symmetry

Facts:

1. $U(1)_{B-L}$ is the only anomaly-free $U(1)$ unless exotic fields are added.

(Caveat: true only for family-independent charges)

2. $U(1)_{B-L}$ cannot have B_3 as a remnant discrete symmetry (see later).

We generalize it to $U(1)_{B-x_iL}$. (No exotic fields are added.)

$U(1)$ charge	1st	2nd	3rd	
$z[Q]=-z[U^c]=-z[D^c]$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	family-independent
$z[L]=-z[N^c]=-z[E^c]$	$-x_1$	$-x_2$	$-x_3$	family-dependent
$z[H_u]=-z[H_d]$	0			
$z[S_1]=-z[S_2]$	$?$			to be determined

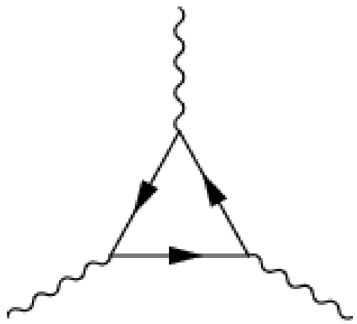
What we need to show about $U(1)_{B-x_iL}$

1. It is anomaly-free
2. It has B_3 as a remnant discrete symmetry

Condition for anomaly-free $U(1)_{B-x_iL}$

[Ex] $SU(2)_L$ - $SU(2)_L$ - $U(1)_{B-x_iL}$ anomaly

(z: $U(1)$ charge)



$$
\begin{aligned}
& A_{2-2-1'} \\
= \quad & N_C \times (3 \times z[Q]) + (z[L_1] + z[L_2] + z[L_3]) + (z[H_u] + z[H_d]) \\
= \quad & N_C \times (3 \times 1/3) + (-x_1 - x_2 - x_3) + (0 + 0) \\
= \quad & 0
\end{aligned}
$$

Anomaly-free condition : $x_1 + x_2 + x_3 = 3$ (1)

(With this, all anomaly conditions are satisfied.)

Family-independent case ($x_1 = x_2 = x_3$) : $x_i = 1$ only ($U(1)_{B-L}$)

Remnant Z_N from a $U(1)$ gauge symmetry

As $U(1)$ is spontaneously broken by $\langle S \rangle$, it leaves Z_N as a remnant.

$$U(1) \;\rightarrow\; Z_N$$

Relation between $U(1)$ and Z_N :

With integer $U(1)$ charges (by hypercharge shift and normalization),

(i) $N = |z[S]|$ (G.C.D. for multiple S)

(ii) $\underbrace{q[\text{field}]}_{Z_N} = \underbrace{z[\text{field}]}_{U(1)} \mod N$

Condition for $U(1)_{B-x_iL} \longrightarrow B_3$

	$B-x_iL$	$6Y$	$(B-x_iL)-2Y$	Z_3	B_3
Q	$1/3$	1	0	0	0
U^c	$-1/3$	-4	1	1	1
D^c	$-1/3$	2	-1	-1	-1
L_i	$-x_i$	-3	$1-x_i$	$1-x_i \bmod 3$	1
N_i^c	x_i	0	x_i	$x_i \bmod 3$	0
E_i^c	x_i	6	x_i-2	$1+x_i \bmod 3$	1
H_u	0	3	-1	-1	-1
H_d	0	-3	1	1	1
S_1	$z[S_1]$	0	$z[S_1]$		
S_2	$-z[S_1]$	0	$-z[S_1]$		

$$Z_3 \text{ condition} \quad : \quad z[S_1] = -z[S_2] = 3 \tag{2}$$

$$B_3 \text{ condition} \quad : \quad x_i = 3 \times \text{integer} \tag{3}$$

Clearly, no solution for B_3 with family-independent charges ($x_i = 1$).

Family-dependent solutions exist.

$$x_i = (-3, 6, 0),\ (3, 0, 0),\ (9, -3, -3),\ \cdots$$

: Anomaly-free $U(1)_{B-x_i L}$ models with residual B_3 (w/o R-parity)

Caveat: It is possible to have B_3 with family-independent $U(1)$ charges for the MSSM sector, if we allow exotic fields [HL, Luhn, Matchev (2008)].

Constraints that we still need to work out

– Neutrino sector

: complicated due to family-dependent charges and additional contributions (λ, λ', μ', etc)

– Collider limits on Z' gauge boson

: Tevatron dilepton search, LEP contact interaction limit ($e\bar{e} \longrightarrow \ell\bar{\ell}$)

– Etc.

(This talk is about *preliminary* work.)

Flavor-sensitive LHC implications

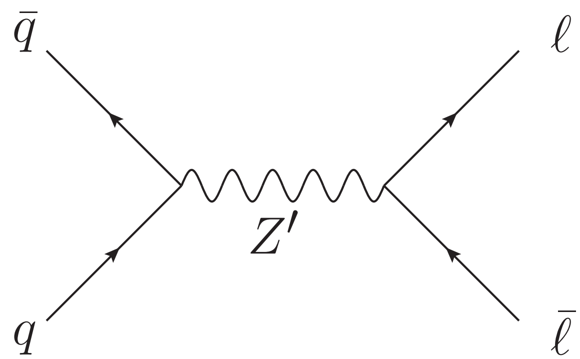
(1) Dilepton Z' resonance

(2) Dilepton $\widetilde{\nu}$ resonance

(3) Complementarity between $\widetilde{\nu}$ and Z' resonances

(1) Dilepton Z' resonance at the LHC

: direct consequence of any gauged $U(1)$



Z' couplings to leptons are flavor-sensitive.

$$\mathtt{Br}(Z' \to e^+e^-) : \mathtt{Br}(Z' \to \mu^+\mu^-) = x_1^2 : x_2^2$$

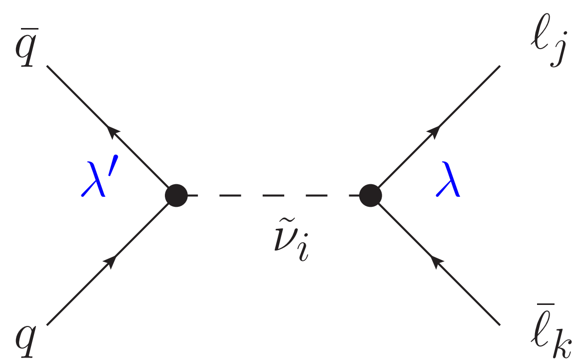
First Z' discovery may depend on which flavor you are looking.

[Ex] For $x_i = (-3, 6, 0)$,

($Z' \to e^+e^-$ events) : ($Z' \to \mu^+\mu^-$ events) $= 1 : 4$

(2) Dilepton $\widetilde{\nu}$ LSP resonance at the LHC

: typical SUSY search channel   (in the absence of R-parity)



Production: $\lambda'_{ijk} L_i Q_j D^c_k$ requires 0 charge for $\widetilde{\nu}_i$. $(z[L_i] + \frac{1}{3} - \frac{1}{3} = 0)$

Decay: $\lambda_{ijk} L_i L_j E^c_k$ requires same charges for ℓ_j and ℓ_k. $(0 + z[L_j] + z[E^c_k] = 0)$

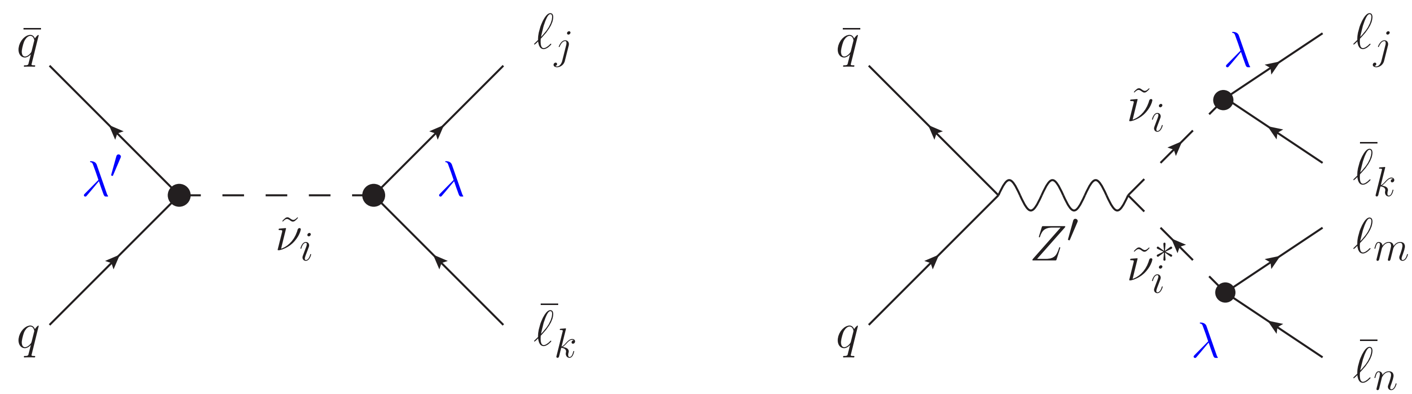
Unlike usual models, some $\widetilde{\nu}$ resonances may be forbidden.

[Ex]   For $x_i = (-3, 6, 0)$ with $\widetilde{\nu}_\tau$ LSP,

Diagonal resonance: $\widetilde{\nu} \to e^+ e^- \ (\lambda_{311}),\ \mu^+ \mu^- \ (\lambda_{322})$ are allowed.

Off-diagonal resonance: $\widetilde{\nu} \to e^+ \mu^- \ (\lambda_{312})$ is forbidden.

(3) Complementarity between $\widetilde{\nu}$ and Z' (di-$\widetilde{\nu}$) resonances at the LHC



If $z[\widetilde{\nu}] \neq 0$, 2-lepton $\widetilde{\nu}$ LSP resonance is forbidden.

How can we see SUSY signal in this case?

It will guarantee $\widetilde{\nu}$ LSP coupling to Z' instead. ($\longrightarrow$ 4-lepton Z' resonance)

2-lepton $\widetilde{\nu}$ resonance and 4-lepton Z' resonance are complementary in SUSY search.

Summary

Summary

1. $U(1)$ for absolute proton stability requires family-dependent charges.

$$U(1)_{B-x_iL} \;\longrightarrow\; B_3$$

(Caveat: R-parity is OK. Other physics can address dim 5 operators.)

2. This implies flavor-sensitive LHC signals.

(1) Z' discovery reach ($Z' \longrightarrow \ell\bar{\ell}$) may depend on lepton flavor.

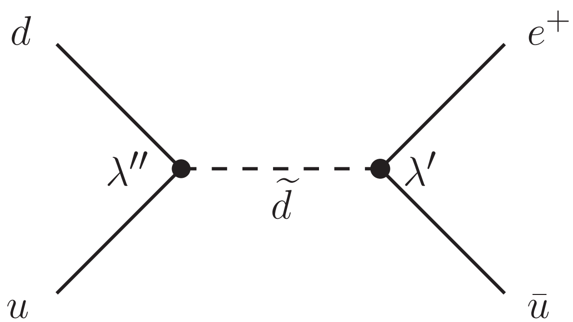
(2) $\widetilde{\nu}$ resonance ($\widetilde{\nu} \longrightarrow 2\ell$) may not have off-diagonal resonances.

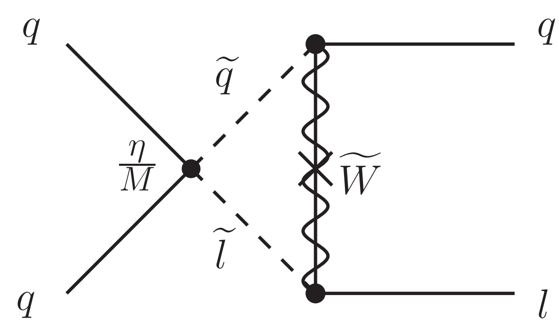
(3) 2-lepton ($\widetilde{\nu} \longrightarrow 2\ell$) and 4-lepton ($Z' \longrightarrow 2\widetilde{\nu} \longrightarrow 4\ell$) resonances are complementary in searching for the $\widetilde{\nu}$ LSP (SUSY signal).

Connection between “Proton stability” & “Flavor physics” in SUSY

Backup slides

Proton decay





[Dim 4 L violation $\&$ Dim 4 B violation]

$\lambda LLE^c + \lambda' LQD^c \;\&\; \lambda'' U^c D^c D^c$

[Dim 5 $B\&L$ violation]

$\frac{\eta_1}{M} QQQL + \frac{\eta_2}{M} U^c U^c D^c E^c$

To satisfy $\tau_p \gtrsim 10^{29}$ years,

Dim 4: $|\lambda_{LV} \cdot \lambda_{BV}| \lesssim 10^{-27}$ (if one is 0, the other can be sizable)

Dim 5: $|\eta| \lesssim 10^{-7}$ $($for $M = M_{Pl})$ [Weinberg (1982)]

Z'-mediated FCNC in lepton sector?

Assume family-dependent $U(1)$ charges.

$$\begin{aligned}
(Z'\text{-fermion-fermion interaction}) &= \bar{\psi}_L \gamma_\mu Q_L \psi_L \\
&= \underbrace{\bar{\psi}_L V_L^\dagger}\,\underbrace{V_L \gamma_\mu Q_L V_L^\dagger}\,\underbrace{V_L \psi_L} \\
&= \bar{\psi}'_L \gamma_\mu Q'_L \psi'_L
\end{aligned}$$

$$Q_L = \begin{pmatrix} a & & \\ & b & \\ & & c \end{pmatrix} \rightarrow Q'_L = \begin{pmatrix} d & (\#) & (\#) \\ (\#) & e & (\#) \\ (\#) & (\#) & f \end{pmatrix}$$

FCNC can occur if $V_L \neq 1$.

$$\begin{aligned}
\text{(fermion mass)} &= \bar{\psi}_L m \psi_R \\
&= \underbrace{\bar{\psi}_L V_L^\dagger}\,\underbrace{V_L m V_R^\dagger}\,\underbrace{V_R \psi_R} \\
&= \bar{\psi}'_L m' \psi'_R
\end{aligned}$$

$$m = \begin{pmatrix} m_{11} & (m_{12}) & (m_{13}) \\ (m_{21}) & m_{22} & (m_{23}) \\ (m_{31}) & (m_{32}) & m_{33} \end{pmatrix} \quad \rightarrow \quad m' = \begin{pmatrix} m_1 & & \\ & m_2 & \\ & & m_3 \end{pmatrix}$$

If $U(1)$ charges are all different for each family,

$\longrightarrow$ off-diagonal $m_{ij} = 0$ (for $i \neq j$)

$\longrightarrow V_L = 1, \;\; V_R = 1$

(If $x_1 \neq x_2 = x_3$, then $m_{23}, m_{32} \approx 0$ is needed for $V_L \approx V_R \approx 1$.)

$U(1)_{B-x_iL} \;\longrightarrow\; R_2$ [HL, Ma (2010)]

$U(1)_{B-L}$ is not the only possible gauge origin of R-parity.

It is possible to have a family-dependent gauge origin of R-parity.

Then $U(1)_{B-x_iL}$ can help with dim 5 p-decay operators issue.

$$
\begin{aligned}
z[QQQL_i] &= \frac{1}{3}+\frac{1}{3}+\frac{1}{3}-x_i = 1-x_i \\
z[U^cU^cD^cE^c_i] &= -\frac{1}{3}-\frac{1}{3}-\frac{1}{3}+x_i = -1+x_i
\end{aligned}
$$

As long as $x_i \neq 1$, dim 5 p-decay operators are forbidden.

Again, connection between the “proton stability” & “flavor physics”.

Why TeV scale Z'?

$$\begin{aligned}\delta m_H^2(\text{top} + \text{stop}) &\approx (-\Lambda^2 + \cdots) + (\Lambda^2 + \cdots) \\ &\approx -m_{\tilde{t}}^2 \log(\Lambda/m_{\tilde{t}}) + \cdots\end{aligned}$$

D-term contribution to scalar masses:

$$\Delta m_{\tilde{f}_R}^2 = (\frac{2}{3}\sin^2\theta_W \cos 2\beta)\, M_Z^2 + (z[f]z[S])\, M_{Z'}^2$$

If $M_{Z'} \gg 100\ \mathrm{GeV} \longrightarrow m_{\tilde{f}} \gg 100\ \mathrm{GeV} \longrightarrow$ Gauge hierarchy problem comes back.

Z' should be $O(100\ \mathrm{GeV}) \sim \mathrm{O}(1\ \mathrm{TeV})$ in SUSY.

How about dark matter?

Without R-parity, the LSP is not a good DM candidate any more.

Add some hidden sector fields (SM singlets) as DM candidate, which interact with the SM only through $U(1)$.

$$U(1) \;\longrightarrow\; Z_N^{\text{total}} = Z_n^{\text{MSSM}} \times Z_m^{\text{hidden}}$$

with $Z_n^{\text{MSSM}} = B_3$ (for proton) , $Z_m^{\text{hidden}} = U_2$ (for DM).

(This was studied in the family-independent charge case [HL (2008)].)

Lightest U-parity Particle (LUP) can satisfy relic density and direct detection constraints.

New channels: LUP + LUP $\longrightarrow$ SUSY + SUSY

(LSP + LSP $\longrightarrow$ SUSY + SUSY is not allowed unless $m_{NLSP} \approx m_{LSP}$).